Age of the Earth

C. Patterson
California Institute of Technology, Pasadena, California

G. Tilton
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C.

M. Inghram
University of Chicago, Chicago, Illinois

A NEW method for estimating the age of the earth consists of calculating a Pb^{207}/Pb^{206} age from the observed differences between the isotopic composition of recent lead isolated from the surface of the earth where appreciable concentrations of uranium exist and the isotopic composition of lead isolated from iron meteorites where insignificant concentrations of uranium are found (*1–3*).

The method is as follows. Let the isotopic composition of lead in the earth at the time it was formed be $Pb^{204} = 1$, $Pb^{206} = x$, $Pb^{207} = y$, and $Pb^{208} = z$, where x, y, and z are the number of atoms of these isotopes for each atom of Pb^{204}; let the isotopic composition of lead in the earth today be $Pb^{204} = 1$, $Pb^{206} = x'$, $Pb^{207} = y'$, $Pb^{208} = z'$. Then $\Delta Pb^{206} = (x' - x)$ is the amount of radiogenic Pb^{206} generated by U^{238} since the earth was formed, and similarly, $\Delta Pb^{207} = (y' - y)$ is the amount of radiogenic Pb^{207} generated by U^{235}. These amounts of radiogenic leads may be expressed in terms of the present U^{238}/U^{235} ratio, k, the disintegration constants of U^{235} and U^{238}, λ_1 and λ_2, and the period of decay, T, as

$$\frac{y' - y}{x' - x} = \frac{(e^{\lambda_1 T} - 1)}{k(e^{\lambda_2 T} - 1)}.$$

This expression is solved for T.

It is necessary to assume that when the earth was formed, it contained lead with an isotopic composition the same as that in iron meteorites, and that the ratio of lead to uranium has not changed, except for radioactive decay in the surface of the earth, since the surface was formed. On the basis of these assumptions, the values of x and y are measured in the lead from iron meteorites and the values of x' and y' are measured in a sample of the average lead in the earth's crust. The age of the earth calculated in this manner, about 4.5×10^9 yr, is considerably greater than the generally accepted estimate of 3.3×10^9 yr, and this paper is an attempt to view this new value in a proper perspective.

Relationship between meteorites and the earth. There are three main points of interest concerning the general relationship between meteorites and the earth. (i) Most meteoriticists believe that meteorites have heliocentric orbits; the basis for this belief is that the emission spectra of meteor trails indicate a close similarity of chemical composition between meteorites and meteors and that radar and photographic velocity data for meteors may be interpreted to mean that meteors have heliocentric orbits (*4*). (ii) There is apparently a 1-to-1 correlation, within experimental error, for the relative abundances of a large number of nonvolatile elements in meteorites and in the sun (*5, 6*); in addition, meteoritic material may be used to construct planet models that possess the physical and chemical properties of the earth (*6, 7*). (iii) No differences between the isotopic compositions of elements existing in meteorites and the earth have been found thus far, except for the few that can be explained by supposedly known and reasonable differences in conditions involving nuclear reactions or isotopic fractionations (*5*). Thus, there is some evidence for believing that meteorites are components of the solar system, that they as a whole do not represent uncommon and highly differentiated chemical systems relative to the earth, and that there is a uniformity of elemental isotopic compositions in both the earth and meteorites. In view of this, there are several possibilities concerning lead and uranium in meteorites that should not be ignored: namely, that the concentrations of lead and uranium in chondrites may be a rough measure of the concentrations of these elements in the earth as a whole, and that the lead in iron meteorites, which contain insignificant amounts of uranium, may represent the kind of lead that existed in the earth when it was formed.

Recently published measurements of the concentrations of lead and uranium in meteorites are listed in Table 1. Since these data were published another sample of lead, isolated from the sulfide phase of the Henbury, Australia, iron meteorite, has been analyzed in the mass spectrometer, and this analysis is included in Table 1. The isotopic compositions of the leads from both iron meteorites are the same, although one is a coarse octahedrite (and in gallium class I) and the other is a medium octahedrite (and in gallium class II). This would indicate that the isotopic composition of lead in iron meteorites is uniform. The isotopic composition of lead, however, is critically dependent upon relative concentrations, during the chemical his-

Table 1. Lead and uranium in meteorites (*8*).

Sample	U (ppm)	Pb (ppm)	Pb composition		
			206/204	207/204	208/204
Canyon Diablo metal phase		0.37*	9.7*	10.5*	29.3*
Average of iron meteorites	0.001 (*9*) (*10*)				
Canyon Diablo troilite	.009	18	9.41	10.27	29.16
Henbury troilite		5	9.50	10.30	29.26
Modoc total stone	.011	0.9			
Norton County total stone	.010				

* Corrected for about 20-percent terrestrial lead contamination introduced during chemical processing.

tories, of uranium, thorium, and lead, and the necessary exact knowledge of these chemical histories in meteorites is lacking at present. For example, the lead now found in iron meteorites may have been exposed to an environment containing higher concentrations of uranium for an unknown period of time before the meteorites were formed. It is not known whether the lead existing in the earth was exposed to a similar environment. There is no evidence, therefore, that compels us to assume that when the earth was formed it contained lead with the same isotopic composition as that in iron meteorites, although such an assumption is necessary for the age calculations.

For the present, the values in Table 1 can be used to estimate the relative abundances of lead and uranium in chondritic material as about 8×10^{-3} atom per 10^4 atoms of Si and 1×10^{-4} atom per 10^4 atoms of Si, respectively. A detailed study of some trace elements in a large number of iron meteorites (*11*) has shown that extensive, though perhaps systematic, variations in the concentrations of those trace elements occur. For this reason, the values given here might differ somewhat from those chosen as significant after a detailed study of these two elements in meteoritic material has been made. High concentrations of lead and uranium in minor phases such as troilite may produce an uncertainty of a factor of about 2 in the concentrations of these two elements in meteoritic material, since the amounts of these minor phases may vary widely in different portions of the same meteorite, and it is difficult to obtain representative samples. The values given here are probably significant to within a factor of about 5 of meteoritic concentrations, assuming that they do not represent extremes of possible variations. If the earth were made of a material with a chemical composition similar to chondritic meteorites (*6*) or of a material represented by a reasonable combination of iron and stone meteorites (*5*), then the foregoing figures would express the abundances of lead and uranium relative to silicon for the earth as a whole.

Primary radiogenic lead growth pattern in the earth. The isotopic compositions have been determined for a number of leads (*12*) isolated from macro lead minerals occurring in mineralized areas that have supposedly been dated either by macro uranium minerals or by post-Cambrian stratigraphy. If the isotopic compositions of these ore leads are arranged according to the times of mineralization of the veins in which they occur, then there is a rough but obvious regularity: the oldest ore leads are least radiogenic, and the younger and younger ore leads become progressively more and more radiogenic.

Upon this evidence, some investigators have assumed that most ore leads are derived at various times from a system of lead and uranium in which the mean Pb/U ratio has not changed except for radioactive decay since the elements were formed. These investigators feel that this primary radiogenic lead growth pattern in the earth has been determined with sufficient accuracy and is reliable enough to provide both a basis for estimating the times at which ore leads are formed (*3, 13*) and a basis for estimating the age of the elements (*14, 15*). In a statistical treatment of a number of lead ores formed during the last 2×10^9 yr, Collins, Russell, and Farquhar (*15*) have calculated that the rate of radiogenic growth in ore leads should result from a ratio of Pb/U in the earth which is 6.4 by weight at present. They have also calculated the isotopic composition of the average ore lead at various times of formation. For purposes of illustration, the curves calculated by them are reproduced in Fig. 1.

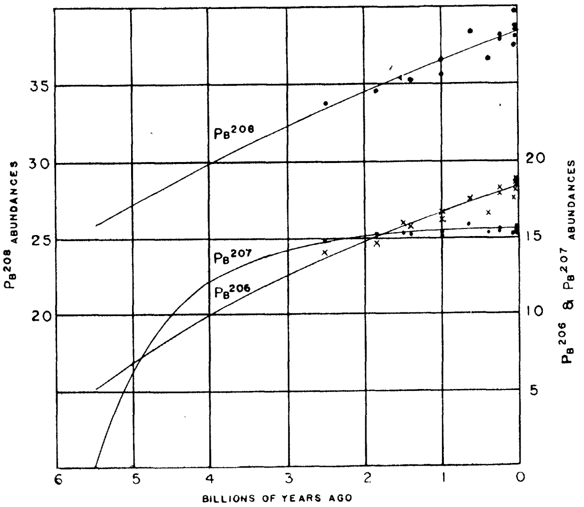

Fig. 1. Average radiogenic lead growth in time, according to Collins, Russell, and Farquhar.

If the primary growth trend is projected back in time to the isotopic composition of the lead we have found in iron meteorites, the time of approximate equality is found to be about 4.5×10^9 yr. This can be interpreted to mean that the calculated lead-uranium and lead-thorium ages for the earth agree with the lead-lead age for the earth, where in the first cases the calculations are based upon the rates of radiogenic growth in lead ores, and in the last case the calculation is based upon a recent sample of average crustal lead.

Although a general trend is apparent in the growth pattern of radiogenic lead in the earth, and we use the Pb/U ratio obtained by Collins, Russell, and Farquhar later in this paper, we do not at present share this same feeling of confidence in the reliability of this primary growth pattern. There is evidence that old and extensive chemical systems exist in the earth which possess widely different ratios of Pb/U, and the effects of the interactions of these systems upon the isotopic compositions of ore leads must still be evaluated. The extension of this fixed growth pattern back to the time of element formation cannot be justified at all and should be viewed with great reservation.

Effects of differentiation of crust from mantle. In simplified terms, the crust of the earth may be considered as a surface one-half covered by a basaltic layer about 10 km thick and the other half covered by a granitic layer about 10 km thick, together with a basaltic layer about 30 km thick underlying the granitic layer. Using commonly accepted values (*16*) for the concentrations of lead and uranium in granites and basalts and assuming that the earth is made of chondritic material, estimates for the fractions of total earth lead and uranium contained in these two layers are given in Table 2.

The figures in Table 2 suggest that an extreme differentiation of uranium relative to lead has occurred within the earth: nearly all of the uranium in the earth is concentrated near its surface and most of the lead is not. This differentiation would tend to make the Pb^{207}/Pb^{206} age calculated for the earth a minimum value.

The effect of such a differentiation process upon the isotopic compositions of leads existing near the earth's surface may be evaluated in the following way. Consider the Pb^{207}/Pb^{206} age of about 4.5×10^9 yr obtained from the difference between meteoritic and terrestrial leads as a rough measure of the period during which mantle differentiation has occurred. The observed radiogenic lead deficiencies in the earth's crust may be obtained by first calculating the relative amounts of radiogenic lead that should have been produced during this period using the present ratio of lead to uranium in the earth's crust, and then comparing these amounts with those obtained by subtracting the isotopic composition of meteorite lead from the isotopic composition of young crustal lead. Unfortunately the present ratio of lead to uranium in the earth's crust, as given by analyses of these two elements in various materials, varies widely and the uncertainty of the quality of the data and the character of the samples is so great that direct measurements cannot be used at the present time. Perhaps the least objectionable estimate for this ratio may be that of 6.4 obtained by Collins, Russell, and Farquhar, since their assumptions may be sufficiently correct for about the last 1×10^9 yr. From this ratio of lead to uranium, it is calculated that 9.9 and 5.6 atoms of radiogenic Pb^{206} and Pb^{207} per atom of Pb^{204} should have been formed in the earth's crust during the last 4.5×10^9 yr. The isotopic compositions of leads isolated from oceanic deposits (*17*), which are mentioned later in this paper, may constitute an experimental determination of the isotopic composition of the average lead in the earth's crust. The differences between the isotopic composition of this lead and meteoritic lead indicate that 9.5 and 5.4 atoms of radiogenic Pb^{206} and Pb^{207} per atom of Pb^{204} exist in the earth's crust today.

Table 2. Approximate distribution of lead and uranium in the earth.

Material	Pb (ppm)	Earth's total Pb (%)	U (ppm)	Earth's total U (%)
5 km of granite	10	1	4	50
20 km of basalt	5	3	0.8	40
Interior		96		10

For this fixed period of 4.5×10^9 yr, it is sufficient to calculate the deficiencies of radiogenic lead in the crust of the earth as a function of the rate of transfer of uranium from the interior to the crust by assuming that the rate of this transfer is proportional to the uranium concentration in the interior and that the transfer of lead is negligible. From such a point of view, deficiencies of less than 5 percent of radiogenic Pb^{207} in the crust require that the transfer of uranium be one-half completed in less than 50 million years. Thus, apparently negligible deficiencies of radiogenic Pb^{207} and Pb^{206} exist in the crust, and it would appear that either mantle differentiation effects are minimal, perhaps as a result of large initial transfer rates, or the application of meteoritic concentration data is in error, the amounts of uranium assigned to the whole earth being too low.

Effects of differentiation within the crust. It is important that we recognize the possibility of systematic variations in the ratios of lead to uranium in different crustal materials and the consequent effects of intracrustal differentiation upon the isotopic composition of lead within the crust. In the preceding paragraphs it has been shown that the ratio of lead to uranium in the earth's mantle may be very high (in the range of 50 to 100) and that the isotopic composition of lead in such ultra deep-seated materials should be grossly nonradiogenic. In the lower parts of the crust or in basalts, a few concentration measurements show that the ratio of lead to uranium is about 6. In the

Table 3. Lead and uranium in earth materials.

Sample		Pb (ppm)	U (ppm)	Th (ppm)	Pb/U	206/204	207/204	208/204	References
Plateau basalt (Quaternary)	Today	6.55	0.65	2.02	10.1	18.12	15.45	38.08	
Basalts and gabbros		5	0.8		6				(*19*)
Canadian Shield granite	Today	9.3	2.74	41.9	3.4	20.25	15.65	48.73	(*18*)
	1.06×10^9 yr ago					16.81	15.28	36.02	(*18*)
Granites		10	4		2.5				(*20*)
Calculated average Pb	Today				6.4	18.5	15.6	38.4	(*15*)
Ore	1.06×10^9 yr ago					16.7	15.5	36.3	(*15*)
Red clay (Quaternary)	Today	35.2				18.95	15.76	38.92	(*17*)
Manganese nodule (Quaternary)	Today	3,450				18.91	15.69	38.68	(*17*)

upper part of the crust, or in granites, there are some measurements which show that the ratio of lead to uranium is about 3.

We have determined the concentrations of uranium, thorium, and lead in a sample of Quaternary flood basalt from the Snake River Plains of Southern Idaho. The concentrations of these three elements have also been determined in a pre-Cambrian alaskite granite from the Canadian shield in Ontario (*18*). These measurements constitute the only precise determinations that have been made of the Pb/U ratios in basalts and granites and the only determinations that have been made of the isotopic compositions of leads in such materials. All these data are summarized in Table 3.

The basalt was obtained from R. S. Cannon of the U.S. Geological Survey, Washington, D.C., who, because of his interest and knowledge of these problems, instigated its collection. The sample was collected by G. J. Neuerburg of the U.S. Geological Survey, Pasadena, California, with special concern regarding contamination and alteration. Neuerberg's report is as follows:

> This sample is a gray micro- and macrovesicular basalt from one of the several pressure-ridged flows that occupy the surface of the Snake River Plain. Judging from descriptions given by Stearns *et al.* (1938), it is one of the latest Pleistocene flows that preceded the extrusion of the black, glassier Recent lavas of which the Craters of the Moon is a prime example. The sample comes from a block deep within the textural profile of the flow that was excavated in construction of the Gooding-Shoshone canal, 1.8 mi north of Shoshone on U.S. Highway 93, Lincoln County, Idaho. The sample was collected from the northwest corner of the intersection of the highway and the canal.
>
> The texture is ophitic and the grain size averages 0.30 mm. Sparse microphenocrysts of olivine are set in a felted matrix of plagioclase (labradorite-andesine) and roundish grains of olivine with space-filling brownish augite and ilmenite or titaniferous magnetite; apatite is abundant. Zircon may be present? In a very few places, augite appears to be slightly altered to a dark brown clayey material; otherwise this sample is exceptionally fresh.

His estimate of the mineral composition, together with the chemical composition determined by W. J. Blake of the California Institute of Technology, is given in Table 4.

As Table 3 shows, the lead to uranium ratio of 10 measured in this basalt agrees well with the more qualitative measurements in other basalts and is distinctly greater than the Pb/U ratio observed in granites. If this basalt is considered to be a representative sample of a closed chemical system that has existed during the last 4.5×10^9 yr, then the amount of lead generated during this period by the decay of the uranium and thorium in the basalt may be calculated and compared with the observed amount of radiogenic lead in the basalt that is found by subtracting the nonradiogenic lead originally present. The isotopic composition of this original nonradiogenic lead may be assumed equal to that in iron meteorites. It is found that radiogenic Pb^{206} is 40 percent in excess and radiogenic Pb^{208} is 80 percent in excess in the basalt. It is quite clear from this gross radiogenic imbalance that the basalt may be chemically nonrepresentative of its source material or the rates of reaction and mixing of the basaltic system with other systems, in which the Pb/U ratios are lower, are rapid in terms of billions of years. The isotopic composition of the lead in the basalt, which was formed recently, is nearly identical with the calculated isotopic composition of an average ore lead formed today.

Listed in Table 3 is the ratio of Pb/U found in the granite by direct measurement. This value of 3 agrees with values found indirectly by measurements in other granites and is clearly much lower than the Pb/U ratio in basalts. If this granite is considered to be a representative sample of a closed chemical system that has existed during the last 4.5×10^9 yr and if a radiogenic balance is calculated in the same manner as for the basalt, it is found that radiogenic Pb^{206} is 50-percent deficient and radiogenic Pb^{208} is 80-percent deficient. Again it is clear that the granite may be chemically nonrepresentative of its source material or the granitic chemical system has reacted and mixed at rates that are rapid in terms of billions of years with other systems in which the Pb/U ratios are higher. The isotopic composition of the lead in this granite at the time granite was formed 1×10^9 yr ago was nearly identical with the calculated isotopic composition of an average ore lead formed at this same time.

Table 4. Mineral and chemical composition of the Shoshone basalt.

Mineral	Volume abundance (%)	Element	Weight abundance (%)	Element	Weight abundance (%)
Plagioclase (An_{67-42})	45	SiO_2	46.68	NaO	2.86
Olivine	10	TiO_2	2.95	K_2O	0.89
Augite	40	Al_2O_3	14.53	P_2O_5	1.20
Ore	4	Fe_2O_3	0.75	MnO	0.19
Apatite	1	FeO	12.78	H_2O^-	.01
		MgO	7.66	H_2O^+	.13
		CaO	9.76	Total	100.39

Table 3 shows the isotopic compositions of two leads isolated from two different Quaternary deposits occurring in the deep areas of the Pacific Ocean. The accumulation of lead in these samples during a period of 10^4 to 10^5 years might be considered to occur in such a way that the lead would be representative of an extremely large mass of material consisting of sedimentary rocks, granitic rocks, and basaltic rocks exposed to the weathering cycle. The isotopic compositions of these two leads are identical, although they are from deposits formed by supposedly different mechanisms (*21*) at widely different locations, and they are similar to the calculated isotopic composition of an average ore lead formed today. These oceanic lead samples may represent the average lead presently existing in the earth's crust.

It is remarkable that the isotopic compositions of the leads originally contained in the granite, the basalt, and the sedimentary deposits should be determined by approximately the same pattern of radiogenic lead growth, that this growth pattern should be very similar to the one calculated for an average ore lead, and that it should be independent of large variations of the Pb/U ratios in these kinds of materials that have a widespread occurrence. Thus, despite evidence of extensive and old chemical systems with very different Pb/U ratios existing in states that would strongly inhibit equilibration, there are definite indications that mixing may exert a first-order effect upon the isotopic compositions of leads in the earth's crust. These data, which indicate that there is extensive mixing and that the radiogenic imbalances of the basalt and the granite tend to cancel out, may eventually prove to be typical for most basalts and granites. This would be strong evidence for a differentiation relationship between acidic and basic rocks and create a difficult problem for those granitizationists who would minimize the role of basalts in the origin of granite.

It might be expected that different patterns of transient radiogenic lead growth would be measured as second-order effects superimposed upon the primary radiogenic lead pattern in old rock systems in the crust containing various Pb/U ratios. The nature of these effects would be determined by the influence of rock-forming processes in various phases of the overall geochemical cycles of lead and uranium in the earth's crust. The differences among the isotopic compositions of leads in various earth materials eventually may be instrumental in showing that certain postulated geologic processes are significant, while others are not. The present interpretations of lead data may be materially substantiated or drastically revised in the near future and are regarded as highly speculative now.

Age of the crust from lead ores. Holmes (*22*), Houtermans (*23*), and Bullard and Stanley (*24*) have used the lead ore data obtained by Nier (*25*) with certain assumptions to calculate an age for the earth's crust and the isotopic composition of primordial terrestrial lead. Collins, Russell, and Farquhar (*15*) have extended the set of galena data, repeated the calculations, and obtained values that agree with those calculated earlier. This method of calculating the age of the earth's crust has been widely discussed, a concise example being the paper by Alpher and Herman (*14*).

Nier pointed out in his original communications that the isotopic compositions of galenas varied with age in a manner that was consistent with the theory that the ores were derived from a system that possessed Pb/U and Pb/Th ratios similar to those found in the earth's crust. Following this, Holmes set forth the assumptions that have been used for all the calculations of the age of the earth's crust based on ore lead data. These assumptions are (i) lead had a uniform isotopic composition throughout the earth up to the time the crust was formed; (ii) when the crust was formed, the Pb/U and Pb/Th ratios in different areas varied slightly, were frozen, and did not subsequently vary except for radioactive decay; (iii) each ore lead has been derived from one such area and has not been mixed with lead from any other source; (iv) the time of formation of a galena can be determined either by stratigraphic correlation or by use of uranium minerals, and this is the time the ore was separated from the parent material in which the lead evolved.

If these assumptions are valid, one can express the isotopic composition of the lead in an ore of age t_m by the equations:

$$x_m = a_o - \alpha V_m \, (e^{\lambda t_o} - e^{\lambda t_m}),$$

$$y_m = b_o - V_m \, (e^{\lambda' t_o} - e^{\lambda' t_m}),$$

$$z_m = c_o - W_m \, (e^{\lambda'' t_o} - e^{\lambda'' t_m}),$$

where x_m, y_m and z_m are the abundances of Pb^{206}, Pb^{207}, and Pb^{208} relative to Pb^{204} in the ore; a_o, b_o, and c_0 are the abundances of Pb^{206}, Pb^{207}, and Pb^{208} at t_0, the time the crust was formed; λ, λ', λ'' are the decay constants for U^{238}, U^{235}, and Th^{232}, respectively; V_m is the present-day ratio of U^{235} to Pb^{204} in the parent material from which the ore was derived; W_m is the ratio of Th^{232} to Pb^{204} in the same material; α is the present ratio of U^{238} to U^{235}. To solve for the age of the earth by the method of least squares, values of the parameters are sought which best fit the ore lead data, subject to the assumptions on which the calculation is made. The solutions obtained by the various authors are given in Table 5.

Table 5. Ore lead solutions for the earth's crust.

Author	t_0 (10^9 yr)	a_0	b_0
Holmes (1947)	3.35	10.95	13.51
Houtermans (1947)	2.9	11.52	14.03
Bullard and Stanley (1949)	3.29	11.86	13.86
Collins, Russell, and Farquhar (1953)	3.5	11.83	13.55

Collins, Russell, and Farquhar used 17 galenas from as many different localities, averaging results when replicate determinations existed for the same deposit (erroneously, perhaps, in the case of their ore No. 6). Of the 17 ores used, five are taken as 25 million years old and a total of nine as less than 500 million years old. This weights the data heavily toward the more modern leads with greatly increased chances for the galenas concerned to have passed through successive environments with differing Pb/U ratios or to have been mixed with leads from other sources, violating the assumptions of the calculation. In addition to the difficulty of assessing the time of formation of the galenas, it is of course possible that this age does not represent the time elapsed since the lead was separated from the parent material that produced it.

Some ore leads have been clearly recognized as "anomalous" and have been excluded from the calculations, since no or aberrant solutions would result if they were not. Examples are the leads from Joplin, Missouri, the Worthington and Garson mines at Sudbury, Ontario, and the Colorado Plateaus (*12*). These leads are excessively contaminated by radiogenic lead or result from a marked increase in V_m at some time in the environment in which they evolved. Although "anomalous" leads can be recognized in extreme cases, there are no sensitive means for detecting "slightly anomalous" leads.

Of the ores used by Collins, Russell, and Farquhar, Nos. 2, 5, and 6 can satisfy the parameters and assumptions within quoted errors with assigned ages of 500 million years as well as 50 million years. Their ore No. 9 will satisfy the parameters with any assigned age between 200 and 900 million years.

Other ores used by them do not, individually, satisfy the parameters and assumptions within the quoted errors, unless the assigned ages are significantly altered. "Slightly anomalous" leads may have been included in the age calculations where their effect on the calculated value of t_0 is difficult to assess but might lead to serious error. The exclusion of these "anomalous" leads, when they are so recognized, has not as yet been justified on acceptable theoretical grounds.

The most important and significant point is that the ore lead age calculation depends upon the *scatter* of the individual isotopic compositions about the curves representing the average radiogenic lead growth in time (Fig. 1). If all ore leads fell exactly upon the lines of average growth, no solution for the age of the crust would be possible by this method. Since the calculation is based on these second-order effects, small errors in the underlying assumptions may be capable of introducing large errors into the results. In view of the evidence for extensive mixing, it would seem contrary to the facts to postulate differing frozen Pb/U ratios that have existed for billions of years. The requirements of the assumptions in the ore lead method are so extreme it is unlikely that it should give a correct age.

We have, then, two methods for estimating the age of the earth: the ore method, which gives an age of 3.5×10^9 yr, and the meteorite method, which gives an age of 4.5×10^9 yr. The two methods may measure different "ages" in that the meteorite method measures the time elapsed since uranium was concentrated with respect to lead in the surface of the earth, while the ore method measures the time elapsed since local variations of the Pb/U ratio were established and frozen in the crust. Holmes has indicated a preference for this point of view (*26*). Houtermans has apparently abandoned the significance of the calculations of the [age of the] earth's crust using lead ores (*3*).

Conclusions. The ore lead method for estimating an age uses terrestrial materials but gives rise to serious uncertainty in the determination of the age of the crust. The meteorite method uses a primordial lead of accurately known isotopic composition and gives an accurately determined age but makes use of extraterrestrial materials whose relationship to the earth is uncertain.

There is no evidence that compels us to assume that when the earth was formed it contained lead with the same isotopic composition as that in iron meteorites. The choice of a suitable sample of recent terrestrial lead that may be compared with meteoritic lead is governed mainly by two requirements: namely, the sample should be derived from a closed chemical system of uranium and lead that has existed since the earth was formed, and the sample should be representative of all the lead in this system. Only a limited number of terrestrial lead samples have been isotopically analyzed. All these leads originate from masses of material that comprise only small fractions of the total mass of the earth. Knowledge of the character of these different mass fractions or chemical systems, the concentrations of uranium and lead in them, and the effects of their interactions with one another at various times upon the isotopic composition of lead in them, is very meager. None of the concepts for the geneses of these leads have sufficient foundation in fact to fulfill justifiably the afore-mentioned requirement.

Nearly all analyzed terrestrial lead samples (except those from uranium minerals) that have been isolated from their uranium environments since Tertiary times (*12*) have isotopic compositions that fall within the range $Pb^{206}/Pb^{204} = 18.07$ and $Pb^{207}/Pb^{204} = 15.40$ to $Pb^{206}/Pb^{204} = 18.95$ and $Pb^{207}/Pb^{204} = 15.76$. When any of these leads are compared with the isotopic composition of lead from an iron meteorite, $Pb^{206}/Pb^{204} = 9.41$ and $Pb^{207}/Pb^{204} = 10.27$, a Pb^{207}/Pb^{206} age of approximately 4.5×10^9 yr is obtained. It should be recognized that an approximate age value is sufficient and should be viewed with considerable skeptictism until the basic assumptions that are involved in the method of calculation are verified.

References and Notes

1. We discussed the essentials of this paper at a Conference on *Application of Nuclear Processes to Geological Problems* sponsored by the NSF and NRC, at Geneva, Wis., Sept. 1953. We gratefully acknowledge the cooperation and assistance by our colleagues, especially R. S. Cannon and G. J. Neuerburg of the U.S. Geological Survey and W. J. Blake of the California Institute of Technology. The portion of the work undertaken at the California Institute of Technology was supported by the U.S. Atomic Energy Commission, contract AT(11-1)-208.
2. C. Patterson, G. Tilton, and M. Inghram, *Bull. Geol. Soc. Amer.* **64**, 1461 (1953).
3. F. Houtermans, *Nuovo cimento* **10**, 1623 (1953).
4. F. Whipple, Harvard University, private communication.
5. H. Brown, *Revs. Mod. Phys.* **21**, 625 (1949).
6. H. C. Urey, *The Planets* (Yale Univ. Press, New Haven, Conn., 1952).
7. H. Brown and C. Patterson, *J. Geol.* **56**, 85 (1948) ; H. C. Urey and H. Craig, *Geochim. et Cosmochim. Acta* **4**, 36 (1953).
8. C. Patterson *et al., Phys. Rev.* **92**, 1234 (1953).
9. G. Davis, *Am. J. Sci.* **248**, 107 (1950).
10. W. Aroll, R. Jacobi, and F. Paneth, *Nature* **149**, 235 (1942).
11. E. Goldberg, A. Uchiyama, and H. Brown, *Geochim. et Cosmochim. Acta* **2**, 1 (1951).
12. H. Faul, Ed., *Nuclear Geology* (Wiley, New York, in press).
13. R. Russell *et al., Trans. Am. Geophys. Union* **35**, 301 (1954).
14. R. Alpher and R. Herman, *Phys. Rev.* **84**, 1111 (1951).
15. C. Collins, R. Russell, and R. Farquhar, *Can. J. Phys.* **31**, 402 (1953).
16. K. Rankama and T. G. Sahama, *Geochemistry* (Univ. of Chicago Press, Chicago, Ill., 1950).
17. C. Patterson, E. Goldberg, and M. Inghram, *Bull. Geol. Soc. Amer.* **64**, 1387 (1953).
18. G. Tilton *et al., Bull. Geol. Soc. Amer.*, in press.
19. G. Hevesy, R. Hobbie, and A. Holmes, *Nature* **128**, 1038 (1931) ; R. Evans and C. Goodman, *Bull. Geol. Soc. Amer.* **52**, 459 (1941).
20. L. Ahrens, *Geochim. et Cosmochim. Acta* **5**, 49 (1954) ; F. Senftle and N. Keevil, *Trans. Am. Geophys. Union* **28**, 732 (1947).
21. E. Goldberg, *J. Geol.* **62**, 249 (1954).
22. A. Holmes, *Nature* **157**, 680 (1946) and **163**, 453 (1949).
23. F. Houtermans, *Z. Naturforsch.* **2a**, 322 (1947).
24. E. Bullard and J. Stanley, *Veröffentl. d. Finn. Geodatischen Institutes* **36**, 33 (1949).
25. A. Nier, *J. Am. Chem. Soc.* **60**, 1571 (1938) ; A. Nier, R. Thompson, and B. Murphey, *Phys. Rev.* **60**, 112 (1941).
26. A. Holmes, University of Edinburgh, private communication.

Effects of Atomic Explosions on Weather

L. Machta and D. L. Harris

U.S. Weather Bureau, Washington 25, D.C.

EVERY year since the explosion of the first atomic bomb, both the U.S. Weather Bureau and the Atomic Energy Commission have received many letters suggesting that atomic bombs should be used to dissipate hurricanes and tornadoes or otherwise improve undesirable weather. Since the atomic weapons testing program was enlarged in 1951, both agencies have also received complaints from many parts of the world blaming unpleasant weather on the atomic explosions.

Although a casual examination of much of the recent climatic data might appear to indicate that some of the recent anomalous weather has been associated with atomic explosions, a more careful examination of the data does not support the hypothesis that atomic explosions have changed the weather.

When the best available observational evidence and the most plausible theories are considered together, there appears to be no reason for believing that any past atomic explosion at the Nevada Proving Ground has had any significant effect on the weather more than a few miles from the test site.

Historical background. Although witnesses to atomic explosions have sought to find ways in which the awesome events may have altered the weather, few cases have been found in which even local effects occurred. The heat from the fires set by the atomic bomb at Hiroshima produced numerous showers in the moist air overlying the city, and the base surge of the underwater Bikini shot also led to the formation of showers that lasted for 20 to 30 min (*1, 2*).

Most of the clouds from explosions in Nevada have been tracked for several hours by aircraft, but none of the pilots has reported any unusual weather developments during these operations. For greater distances, the atomic cloud has been followed across the United States by means of meteorologic trajectories (*3*), and even though there has been no attempt to make a detailed study of the weather in association with the atomic clouds and areas of radioactive fall-